

Discontinuous design of negative index metamaterials based on mode hybridization

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An electric inductor-capacitor (ELC) resonator provides a series of electrical resonances and a pair of ELC resonators leads to the split of each resonance into two modes, i.e., magnetic and electric modes, corresponding to antisymmetric and symmetric current distributions. With the meticulous design of the ELC resonator, we can achieve a negative index metamaterial through mode hybridization by overlapping the first electric resonance mode and the second magnetic resonance mode. Such non-connected designs may offer opportunities to achieve three-dimensional negative index metamaterials.

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Metamaterials (MMs), formed by artificially designed, subwavelength building blocks, have already brought us various, unexpected phenomena and applications, such as negative refraction, sub-diffractive imaging, and cloaking, etc.^{1–6} Up to now, in most of the negative-index-metamaterial (NIM) designs, continuous metallic components, are adopted to provide negative ϵ led by a Drude-shape electric response, and negative μ is realized by some specifically-designed magnetic resonator, which generally shows a Lorentz-shape magnetic response.^{7–13} There also have been some non-connected negative index metamaterials (NIMs) achieved via engineering the electric and magnetic resonances of the same plasmon mode to realize a spectral region, in which permittivity and permeability are simultaneously negative. Zhou *et al.*¹⁴ proposed to utilize the interaction between the neighboring cut-wires in plane to lower the electric resonance frequency so the band for negative permeability can be settled within the region of negative permittivity since the electric resonance is much stronger and much wider than the magnetic one; they have both numerically and experimentally investigated a possible design, “H-shaped” cut-wire pair, which showed an exact negative index band.¹⁵ However, the disadvantage of such a mechanism is the severe requirement of geometry parameters to guarantee a strong enough interaction between neighboring unit cells to shift the electric resonance frequency below the magnetic frequency. Recently, Kante *et al.* offered a scheme for designing a non-connected negative index metamaterial by inverting the hybridization of plasmon modes via misalignment of paired cut-wires.^{16,17} However, it is easy to see that the misalignment of cut wires will undoubtedly increase the size of the unit cell and may hurt the “subwavelength” property of such metamaterials further.

In this paper, we propose a configuration to obtain a negative index metamaterial with pure discontinuous elements, i.e., a pair of electric-coupled inductor-capacitor (ELC) resonator.^{18,19} As well known, a single ELC res-

onator provides a series of electric resonances, the first two of which can be denoted as modes $|\omega_1\rangle$ and $|\omega_2\rangle$ respectively. On the other hand, when two original individual resonators compose a paired system, a hybridization of plasmon modes^{20,21} for each individual resonator occurs, forming two separate eigenmodes. Generally, the eigenmode at the lower frequency is magnetic corresponding to antiparallel currents, while the electric eigenmode with parallel currents is at a higher frequency (i.e., $|\omega_{mi}| < |\omega_{ei}|$), where i represents the order of the resonance mode). Therefore, an intuitive scheme for achieving a NIM is to adopt a paired system of ELC resonators and try to overlap the spectral regions of negative permittivity, ϵ , of the first resonance and negative permeability, μ , of the second resonance.

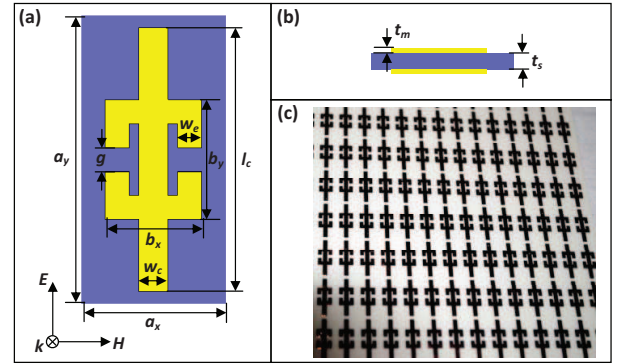


FIG. 1: (Color online) (a) Front view and (b) top view to the schematic of a unit cell of the discontinuous NIM design. (c) A photo of the experimental sample. $a_x = 6$ mm, $a_y = 12$ mm, $b_x = 4$ mm, $b_y = 5$ mm, $w_c = 1.2$ mm, $l_c = 11$ mm, $w_e = 1$ mm, $g = 1$ mm, $t_s = 0.787$ mm, $t_m = 34$ μ m.

Figure 1 presents a possible design of NIM, based on the above-mentioned mechanism through a pair of ELC resonators. The ELC resonator can be considered as a

transformed E1 structure in Ref. 19, with the central bar elongated. Essentially, it is a combination of an E1 structure and a cut wire. We will show below that such a design makes negative ϵ for $|\omega_{e1}\rangle$ overlap with negative μ for $|\omega_{m2}\rangle$ sufficiently for negative n . The schematic of mode-hybridization-mechanism through a pair of ELC resonators for negative n is presented in Fig. 2, which also shows the surface current pattern of each resonance mode specifically for our design. The different thicknesses of the arrows schematically represent the different strengths of the surface currents.

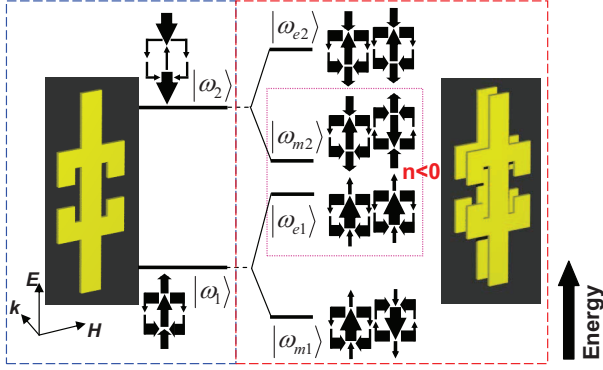


FIG. 2: (Color online) Schematic of our proposed mode-hybridization mechanism to achieve negative index n . Surface current patterns of our designed structure are shown next to the denotation of each mode.

We set our design to work in the gigahertz (GHz) region with the corresponding parameters shown in the caption for Fig. 1. The structure is patched on Rogers 4003 printed circuit board. A 0.787 mm-thick layer of dielectric ($\epsilon_s = 3.55$ and loss tangent 0.0027) is coated with a 34 μm -thick copper layer on both sides. We characterize the properties of the ELC resonator pair via both numerical simulations and experimental measurements. The simulations are performed with the commercial software package, CST Microwave Studio. The software determines the reflection and transmission information of the structure employing the finite integration technique. In the simulations, only a single unit cell as shown in Fig. 1(a) is taken into account with a periodic boundary condition in x and y directions to mimic an array of ELC resonator pair structure. Two ports are settled at each side of the structure parallel to the x - y plane, respectively. The simulated reflection/transmission (R/T) spectra are shown as dashed curves in Fig. 3(a) and (b). A photograph of the fabricated sample for experimental study is shown in Fig. 1(c).

We measured the transmission and reflection properties of a single-layer structure using an Agilent E8364B PNA network analyzer supplied by a pair of Narda standard gain WR-62 horn antennas as source and receiver. The working frequency is 12.4-18.0 GHz. Through appropriate calibrations, we obtain clean spectra of reflection and transmission as presented in Fig. 3 (a) and (b) with

solid curves. The overall qualitative agreement between simulations and measurements is pretty good. To further demonstrate the properties of this structure, we extract its electromagnetic parameters, i.e., n , ϵ , and μ , from the obtained R/T information by using the well-established retrieval procedure.²²⁻²⁴ In the retrieval, we assume the unit-cell size in z -direction is 2.855 mm by adding a 1 mm-thick air layer on each side of the structure.

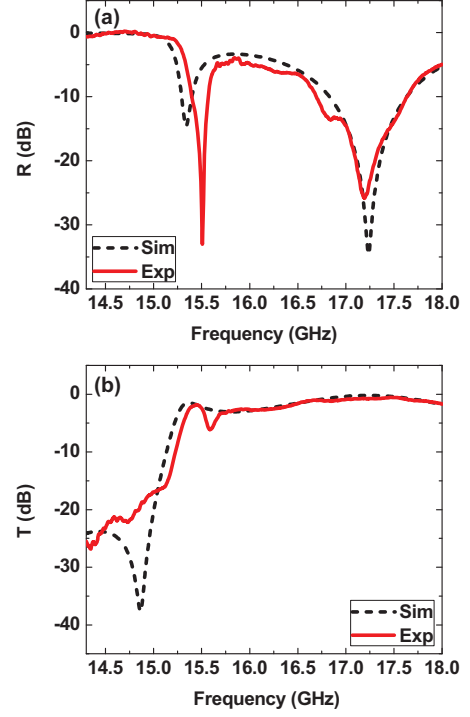


FIG. 3: (Color online) Reflection (a) and transmission (b) spectra for normal incident electromagnetic wave on the designed ELC resonator pair structure: Simulations (black dashed curves) and experiments (red solid curves).

It is clearly seen from Fig. 4 the structure shows a narrow band of negative n with simultaneously negative ϵ and μ around 15.5 GHz, both in simulation and measurement. The dip value of refractive index n by the experiment is as low as -2.4 , compared to -3.1 from the simulation. The simulated and measured permeability μ dips to -3.6 and -2 , respectively, which originates from a strong magnetic resonance, the second order magnetic resonance of our designed ELC resonator pair structure (the first order magnetic resonance occurs at ~ 6.6 GHz, not shown here). The strength of the second magnetic resonance is comparable to that of the first order, with quality factors of about 46 and 55, respectively. Here, we would like to mention that, before any optimization to the design, our structure has the maximum figure of merit (FOM) about 10, which can be improved with further modulation to the parameters. We also have completed a series of simulations by changing l_c in the structure (results not shown here). The original separation of ω_{e1} and ω_{m2} is large with a small l_c . When we increase

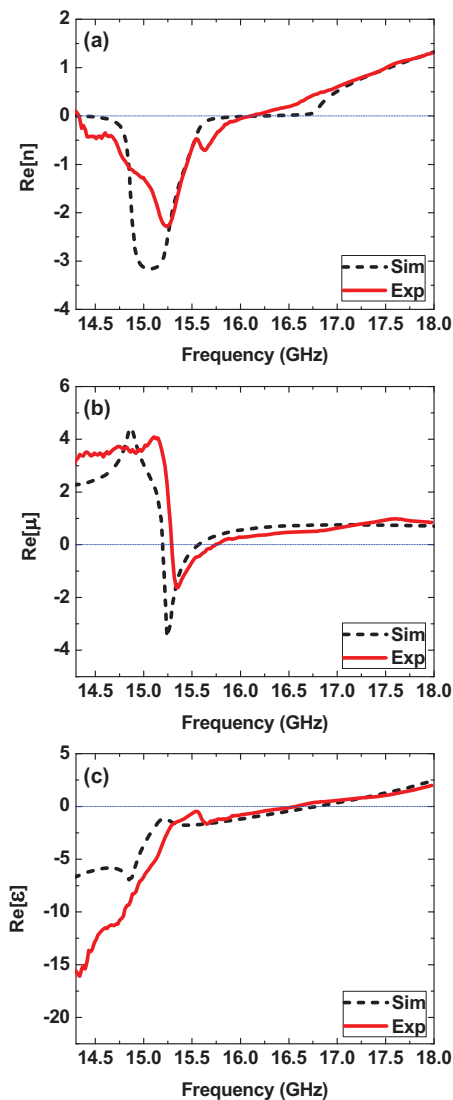


FIG. 4: (Color online) Retrieved (a) refractive index n , (b) permeability μ , and (c) permittivity ϵ of a single-layer of designed ELC resonator pair structure, using the simulated (black dashed curve) and measured (red solid curve) reflection and transmission data.

l_c , ω_{e1} and ω_{m2} become closer and finally, when $l_c = 11$ mm, the second magnetic resonance ($\mu < 0$) overlaps with the first electric resonance ($\epsilon < 0$) giving negative n . This confirms our expectation of the mode hybridization mechanism for NIM designs. In addition, the proposed design or various ELC resonator pair structures, based on mode-hybridization mechanism, may render negative index not only for GHz, but also in high frequency regions and can be used to fabricate three-dimensional metamaterials with negative index of refraction.²⁵

In conclusion, pairing ELC resonators splits each resonance of the original single structure into two modes, i.e., magnetic (lower energy) and electric (higher energy) ones. We propose a mechanism to realize negative index by hybridizing the first electric resonance and the second magnetic resonance of a paired ELC resonator system. Both numerical simulation and experimental measurements for an ELC resonator pair design have confirmed our expectation for a band showing a negative refractive index. Such a category of designs is based on isolated components, which shall benefit the realization of high dimensional negative index metamaterials. The idea may also work in high frequency regimes, even at optical wavelengths with various intriguing designs.

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